Wobblers and Rayleigh-Taylor Instability Mitigation in HIF Target Implosion

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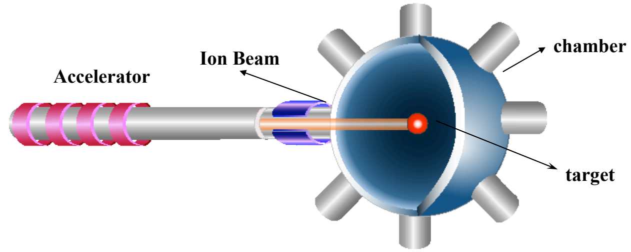
Purpose



Improve HIB illumination non-uniformity of wobblers' initial imprint, which induces implosion non-uniformity

Background

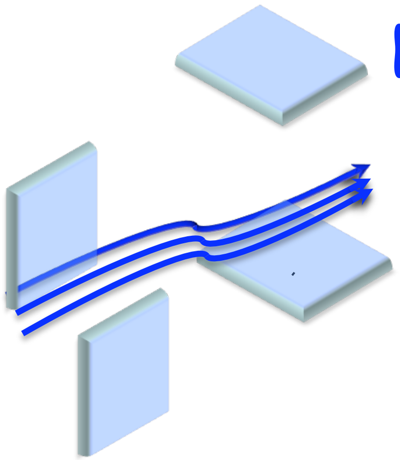
Precisely controllable HIB: pulse shape, particle energy, beam axis, etc.

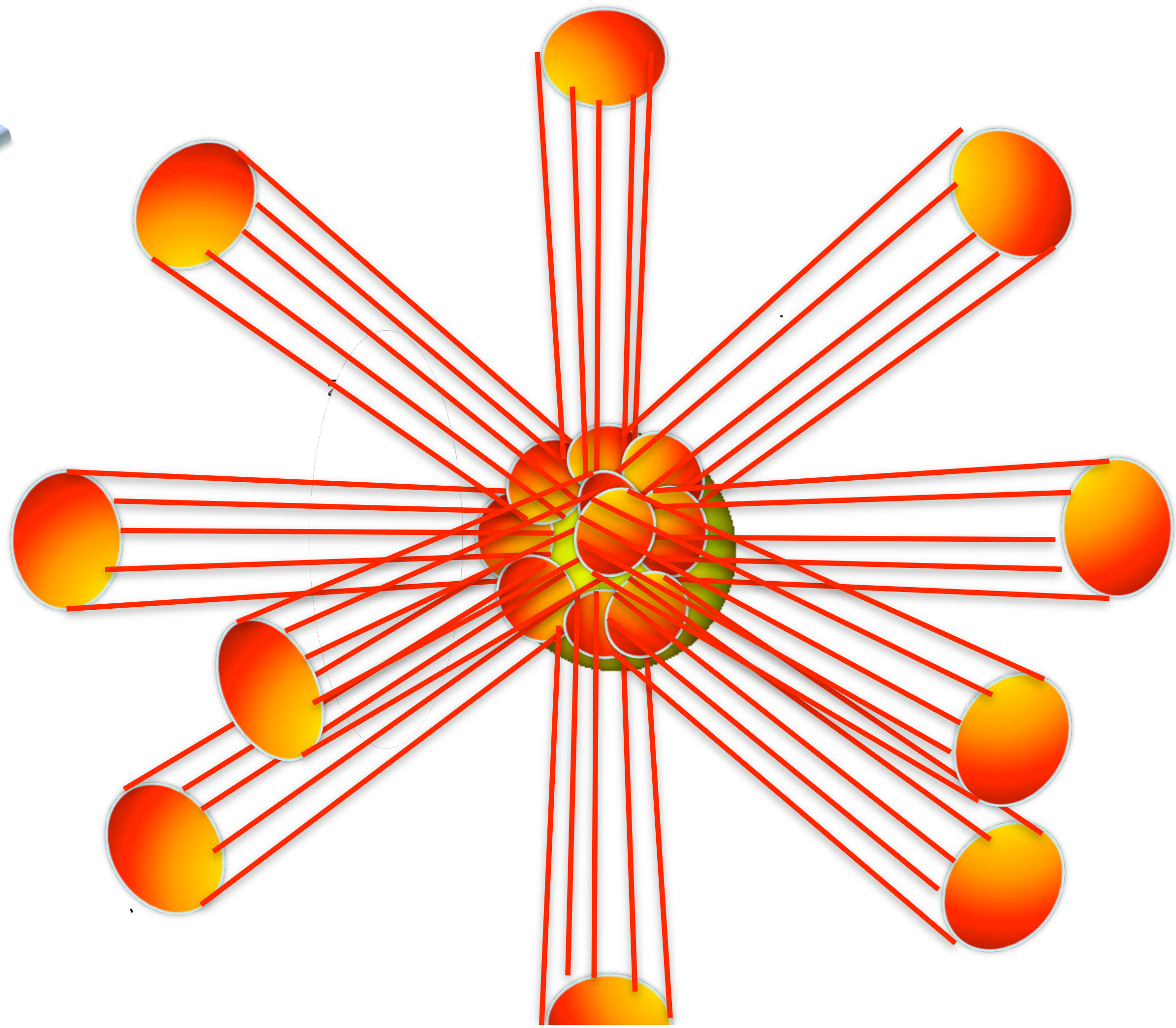
Wobbling HIBs were proposed to smooth HIB illumination nonuniformity & R-T growth reduction. <- M. Basko, et al., /S.Kawata, et al., /J. Lunge, et al., /H. Qing, / A. Friedman, etc.

J. Lunge & G. Logan found a very-good uniformity of wobbling HIBs illumination for time-averaged HIBs on a target.

-> A large HIBs-illumination nonuniformity by the Initial imprint ~ 15% or
-> Initial imprint should be reduced.

Wobbling Heavy Ion Beams may reduce the R-T growth.





Background

PRL 104, 254801 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Centroid and Envelope Dynamics of High-Intensity Charged-Particle Beams in an External Focusing Lattice and Oscillating Wobbler

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(Received 14 January 2010; published 22 June 2010)

The centroid and envelope dynamics of a high-intensity charged-particle beam are investigated as a beam smoothing technique to achieve uniform illumination over a suitably chosen region of the target for applications to ion-beam-driven high energy density physics and heavy ion fusion. The motion of the beam centroid projected onto the target follows a smooth pattern to achieve the desired illumination, for improved stability properties during the beam-target interaction. The centroid dynamics is controlled by an oscillating ''wobbler,'' a set of electrically biased plates driven by rf voltage.

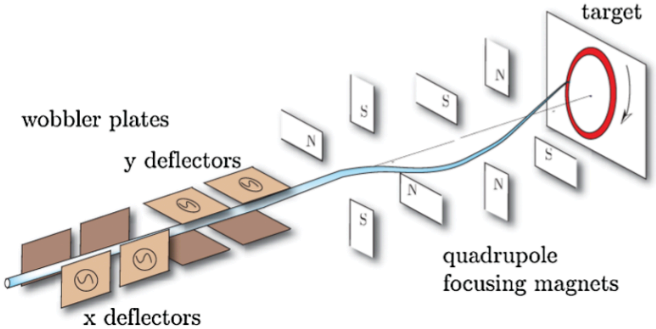
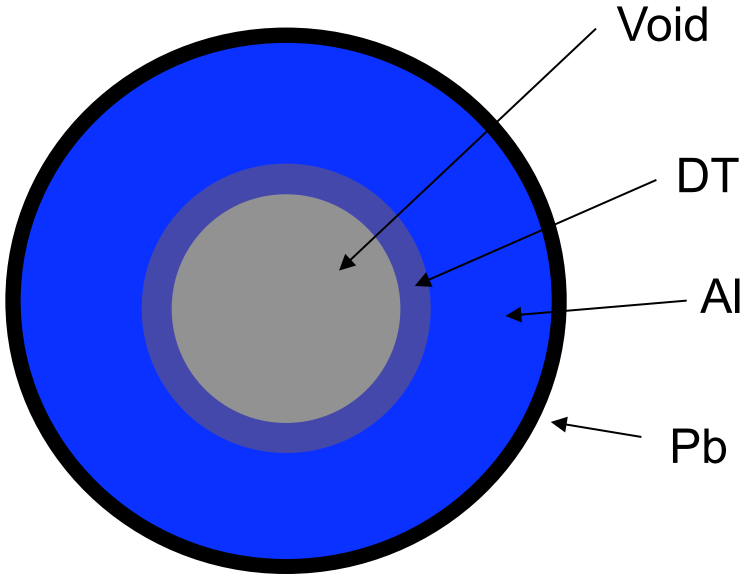
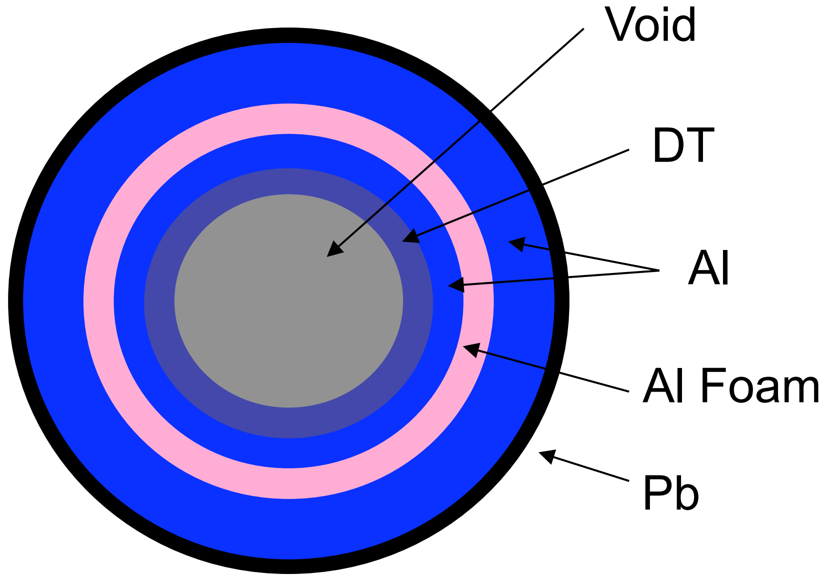


FIG. 1 (color). Quadrupole focusing lattice and wobbler system. The motion of the centroid projected onto the target follows a smooth pattern in order to achieve uniform illumination over a suitably chosen region of the target.

Background

Examples of HIF target design

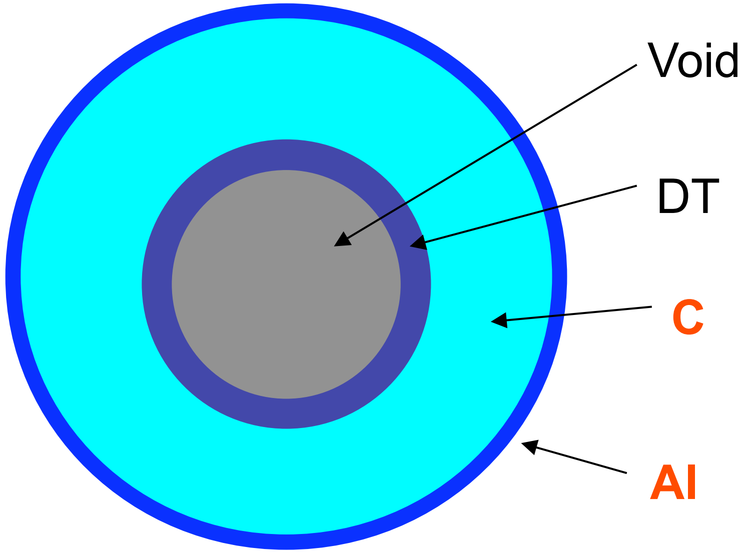




Direct-indirect hybrid implosion

HIB input energy is 4MJ,

-> Gain ~45.



HIB input energy is 1.8MJ,

-> Gain ~100.

PHYSICS OF PLASMAS **15**, 072701 (2008)

Direct drive heavy-ion-beam inertial fusion at high coupling efficiency

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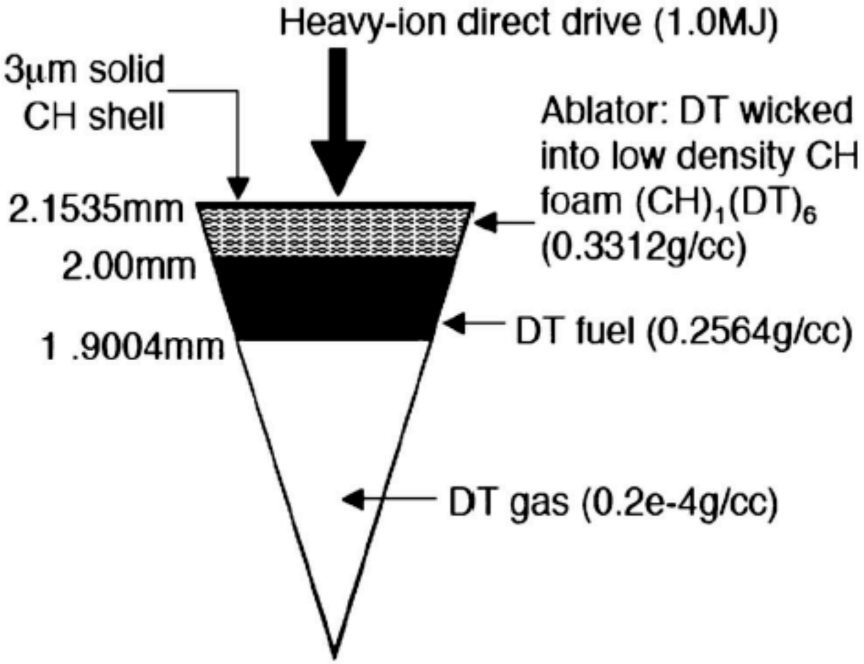
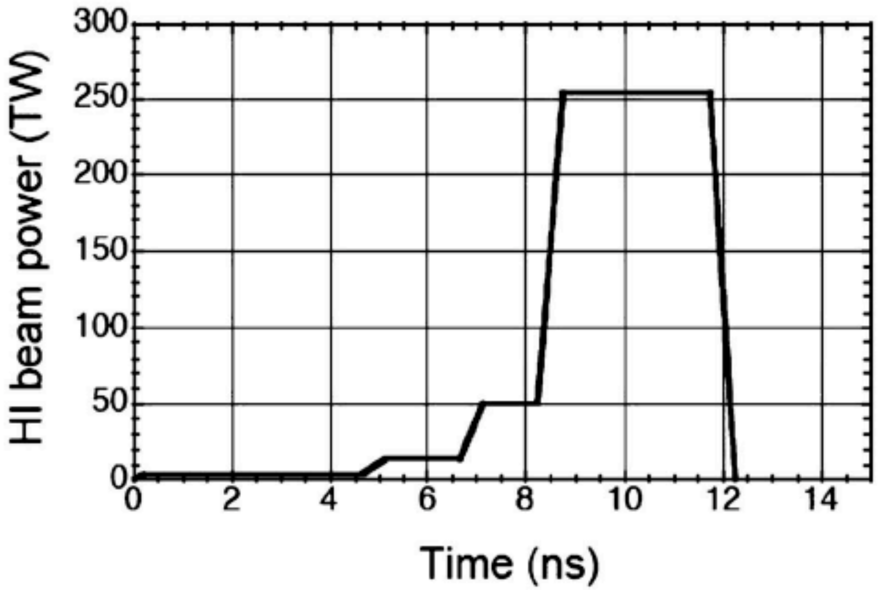
[2]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*



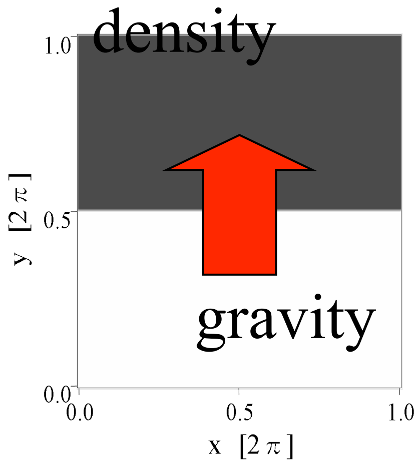


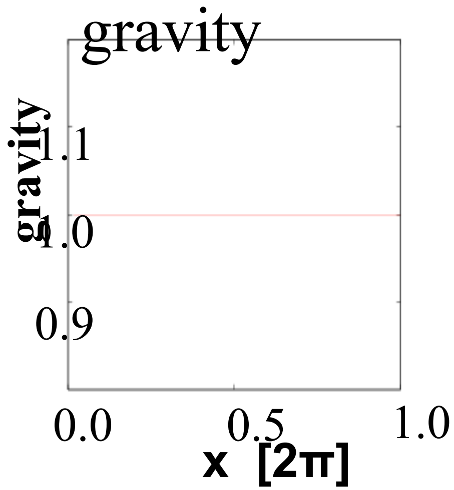
high coupling efficiencies shell kinetic energy/
incident beam energy of 16% to 18%!!!

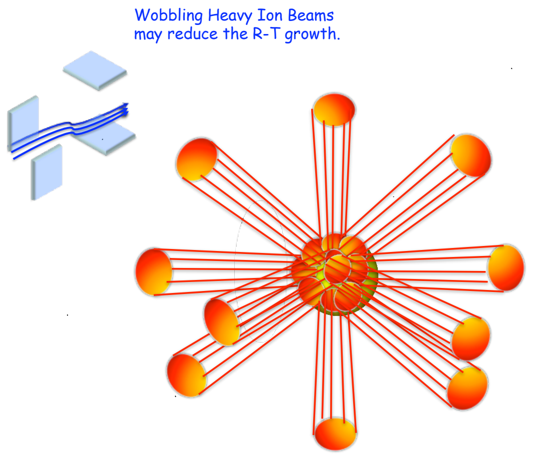
Background

R-T instability growth control by Wobblers

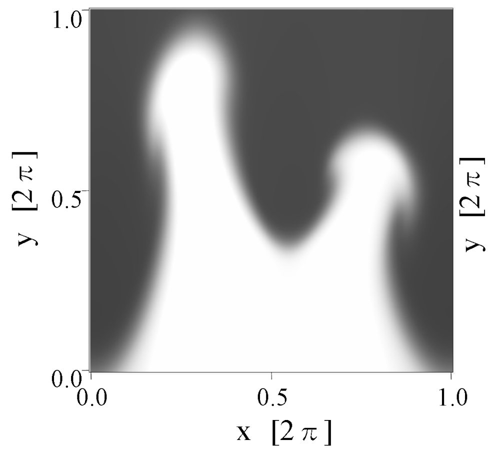
$g = g_0 + \delta g$



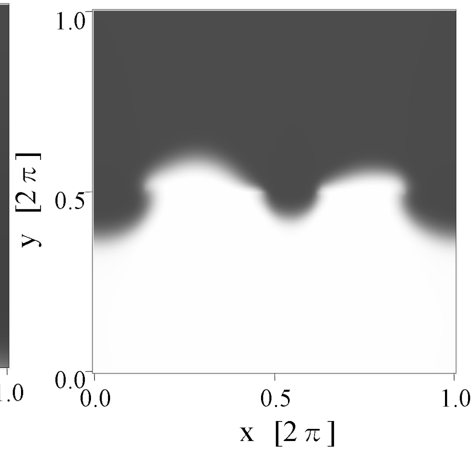




Normal R-T growth



R-T growth under δg oscillation



PHYSICS OF PLASMAS **19**, 024503 (2012)

Dynamic mitigation of instabilities

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(Received 8 December 2011; accepted 19 I

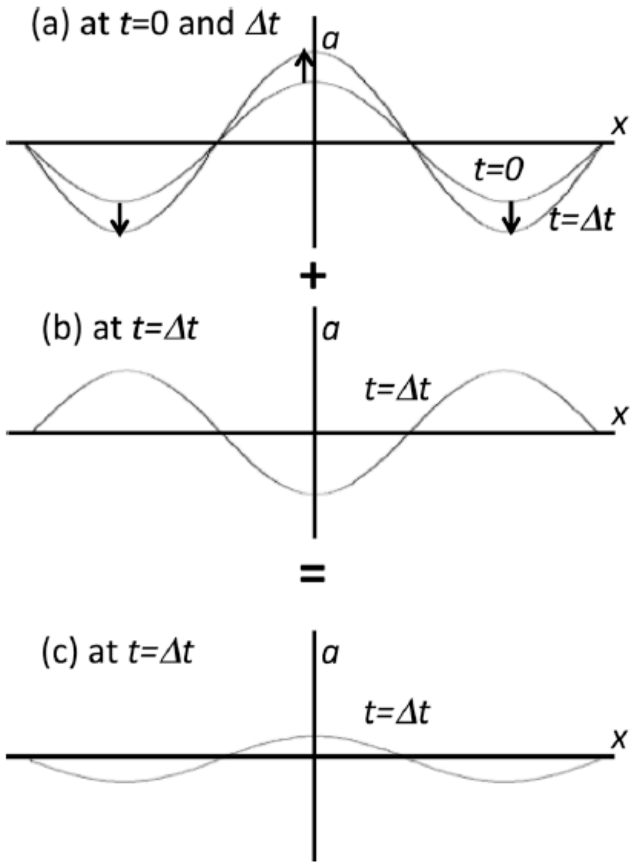
In the paper Phys. Plasmas **18**, 09270

Feedback control is preferable to stabilize the instability; the phase and amplitude are detected.

-> But in plasmas, we can not measure the perturbation phase & amplitude.

-> But we can actively impose the perturbation by the driver itself.
-> this means that we know the phase!

+ In addition, the overall perturbation is the superposition of all the perturbations.



An example concept of feedback control. (a) At $t=0$, a perturbation ...sed. The initial perturbation may grow at instability onset. (b) After ...e feedback control works on the system, another perturbation, which has an inverse phase with the detected amplitude at $t=0$, is actively imposed, so that (c) the actual perturbation amplitude is mitigated very well after the superposition of the initial and additional perturbations.

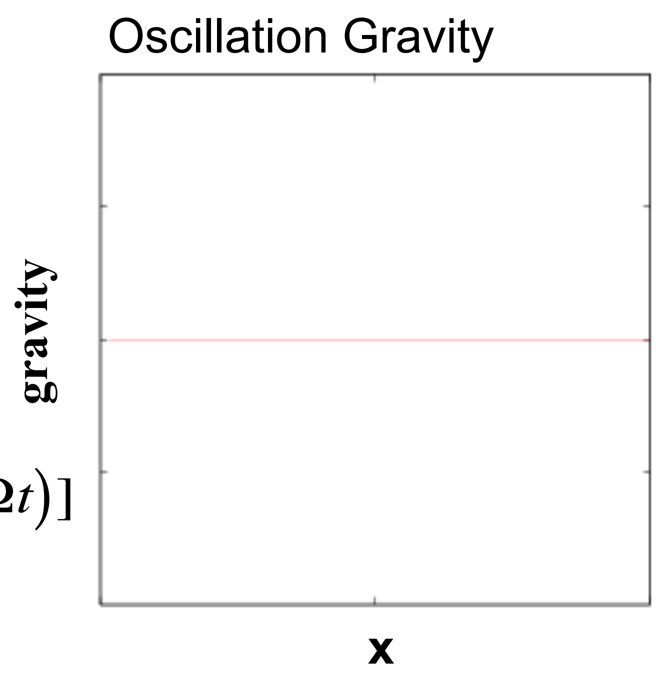
the ism, al, a ation f the n of the le, a the *ican*

Control of RTI - Oscillating gravity -

$$g(x,y,z,t) = g_0 + \delta g(x,y,z,t)$$
$$= g_0 + g_1 f_1(x,y)\exp(-\beta|z|)\exp(i\Omega t)$$

$$w_0 \propto \delta g \Delta t$$
$$\Omega = 2\pi f$$

$$w = \frac{\gamma + i\Omega}{\gamma^2 + \Omega^2} g_1 \exp(ik_x + ik_y)[\exp(\gamma t) - \exp(i\Omega t)]$$



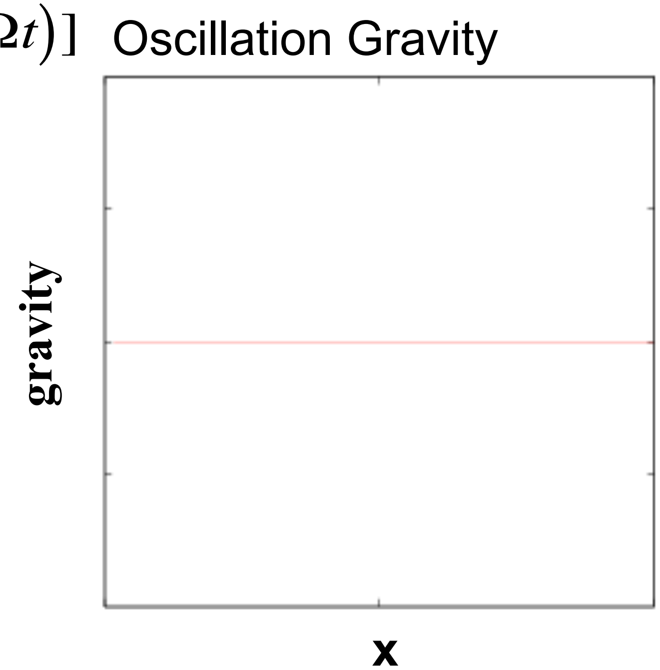
w : *velocity* $\quad \gamma$: *growth rate* $\quad f$: *frequency*

w_0 : *initial velocity* $\quad \delta g$: *non-uniform gravity* $\quad t$: *time*

From the equation, when the gravity oscillation frequency *f* is increased, the RTI perturbation velocity *w* decreases.

Control of RTI - Oscillating gravity -

$$w = \frac{\gamma + i\Omega}{\gamma^2 + \Omega^2} g_1 \exp(ik_x + ik_y)[\exp(\gamma t) - \exp(i\Omega t)]$$



$$|w| \approx \frac{1}{\Omega} g_1 \exp(\gamma t) \qquad for \quad \gamma << \Omega$$

$$|w| \approx \frac{1}{2\gamma} g_1 \exp(\gamma t) \qquad for \quad \gamma = \Omega$$

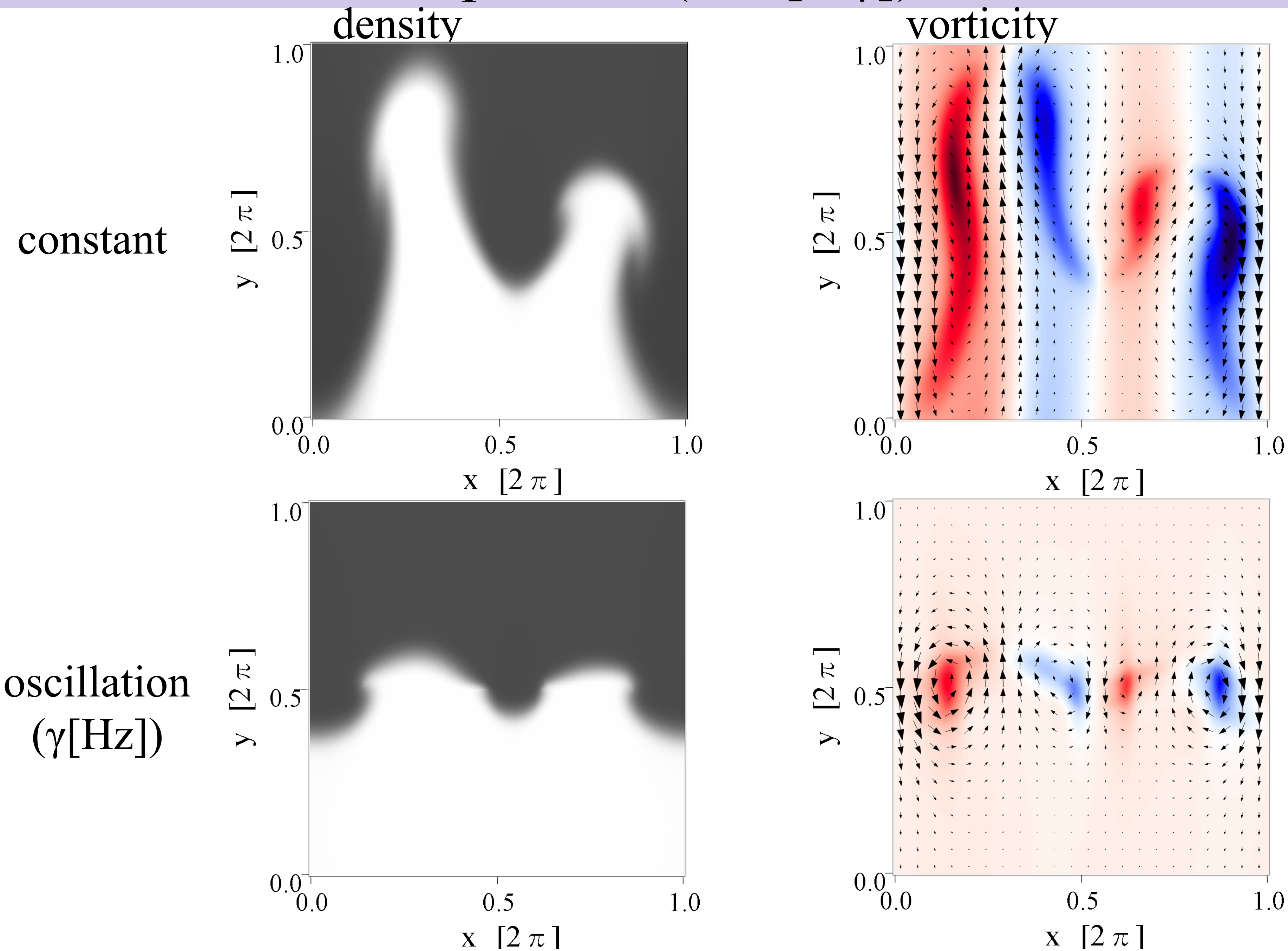
$$Growth\ Reduction\ Ratio \approx \frac{\gamma}{\Omega} \quad for \quad \gamma << \Omega$$

$w : velocity \quad \gamma : growth\ rate \quad f : frequency$

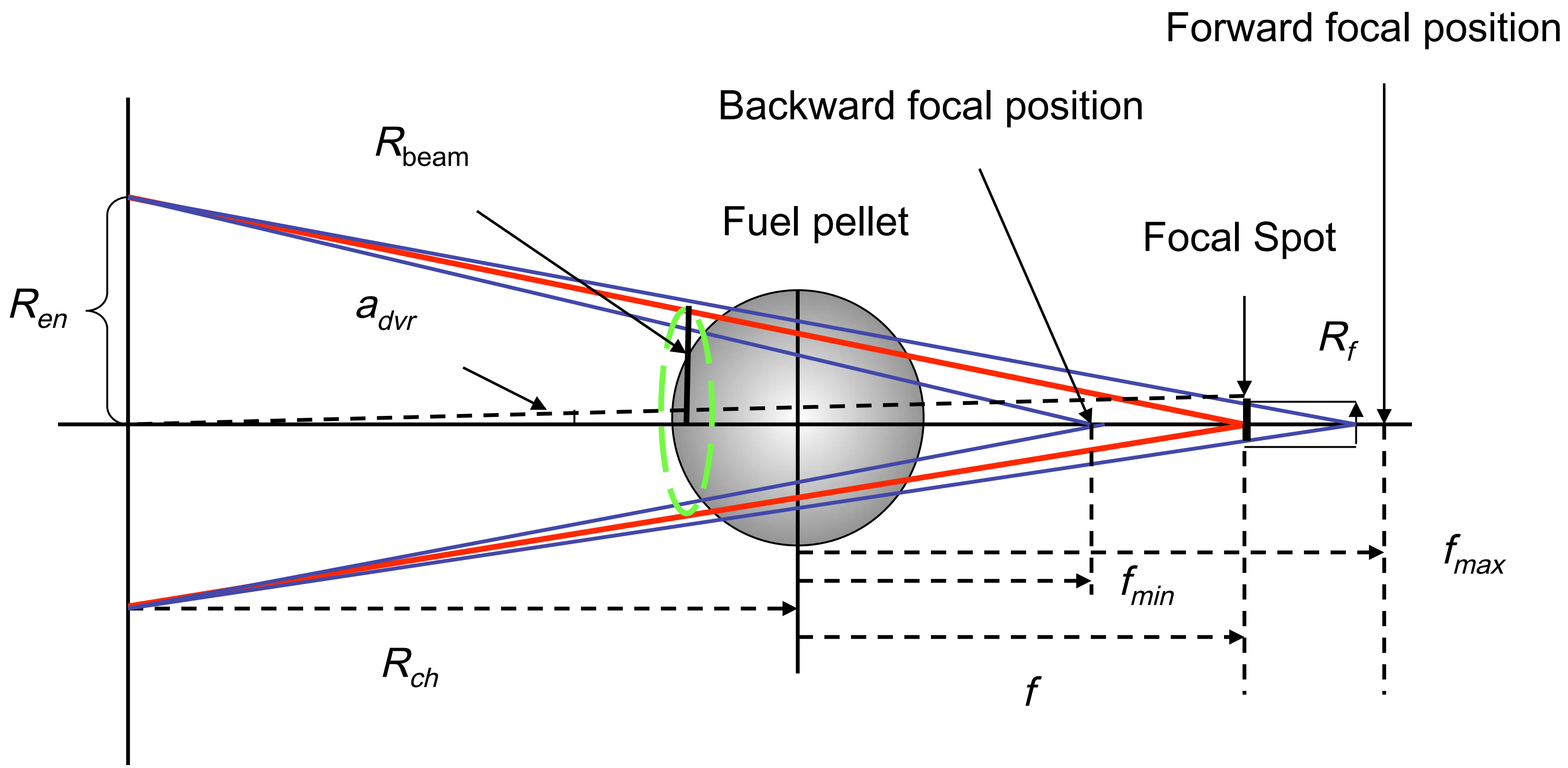
$w_0 : initial\ velocity \quad \delta g : non-uniform\ gravity \quad t : time$

From the equation, when the gravity oscillation frequency *f* is increased, the RTI perturbation velocity *w* decreases.

Multi Mode Comparison (t=5 [1/γ])

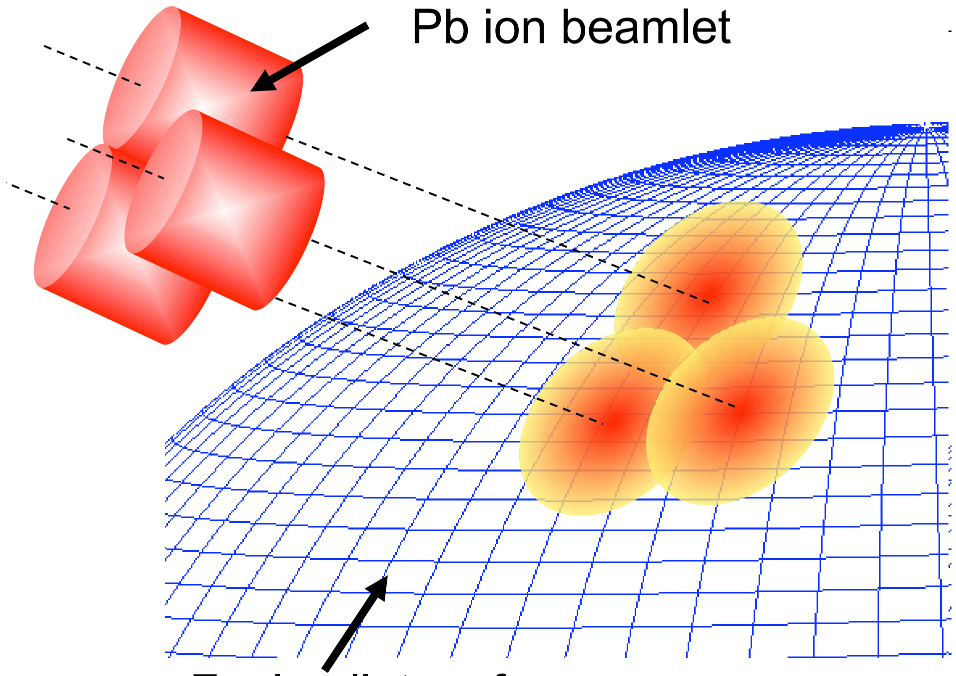


HIB-Fuel pellet interaction

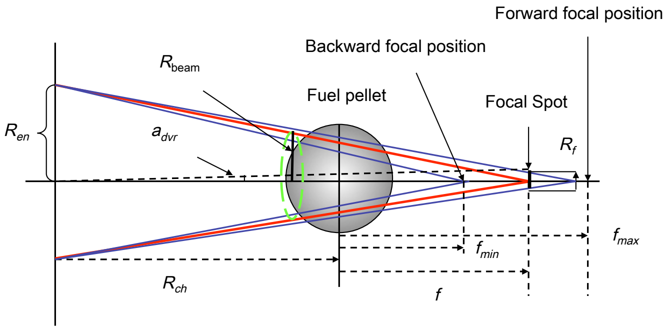


HIB illumination model

2. HIB-Fuel pellet interaction (2)



HIB-Fuel pellet interaction



HIB illumination model

Calculation procedure

1. A beam is divided into many beamlets
2. Calculation of beam particle trajectories
3. Calculation of stopping power
4. Energy deposition on to the fuel pellet

PHYSICS OF PLASMAS **16**, 033109 (2009)

Nonuniformity for rotated beam illumination in directly driven heavy-ion fusion

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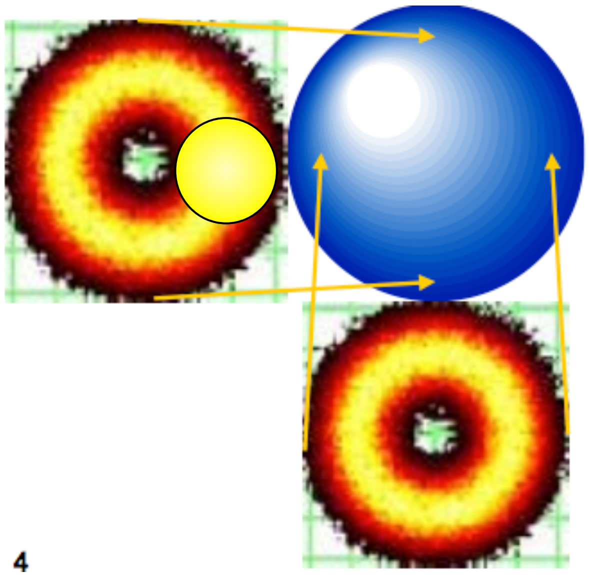
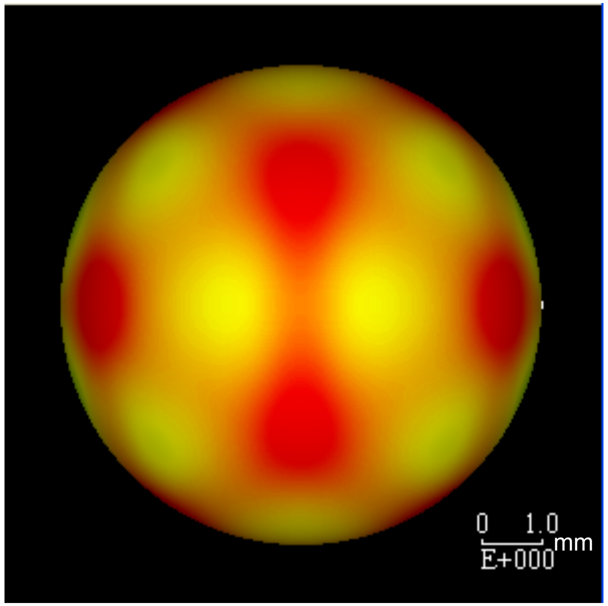
60 HIBs -> <1% HIB illumination non-uniformity

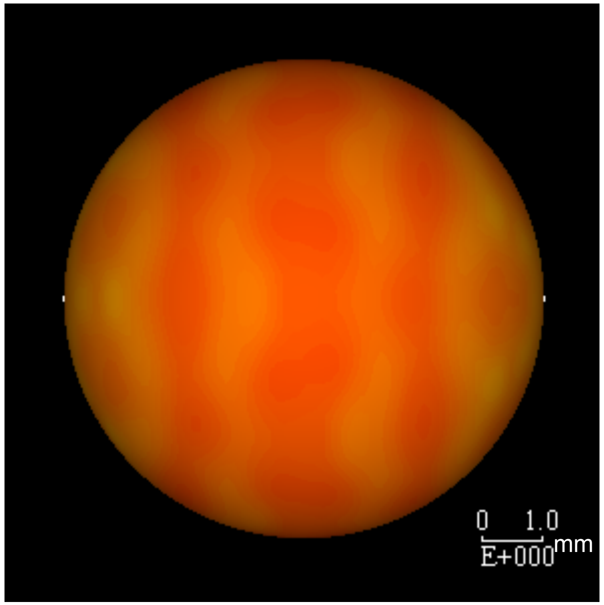




12 beams
Rotation radius 1.9mm
Beam radius 2.6mm
σ_{rms} 8.29%

12-beam

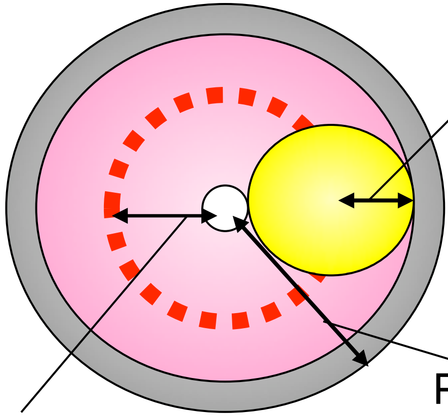
12-HIBs illumination system



32 beams
Rotation radius 1.9mm
Beam radius 2.6mm
σ_{rms} 2.32%

32-beam

32-HIBs illumination system



Parameters

Pb^+ ion beam

Beam number : 32

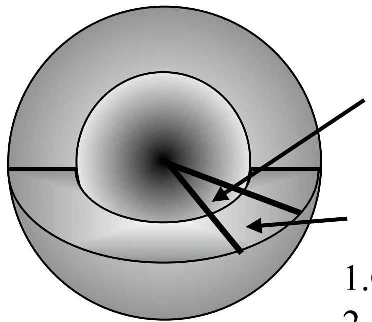
Beam particle energy : 8GeV

Beam particle density distribution : Gaussian

Beam temperature of projectile ions : 100MeV with the Maxwell distribution

External pellet radius : 4.0mm

Pellet material : Al



Al pellet structure

32 HIBs

ref.: Skupsky & Lee, JAP 54(1983)3662.

S. Skupsky, and K. Lee, J. Appl. Phys. **54**, 3662 (1983).

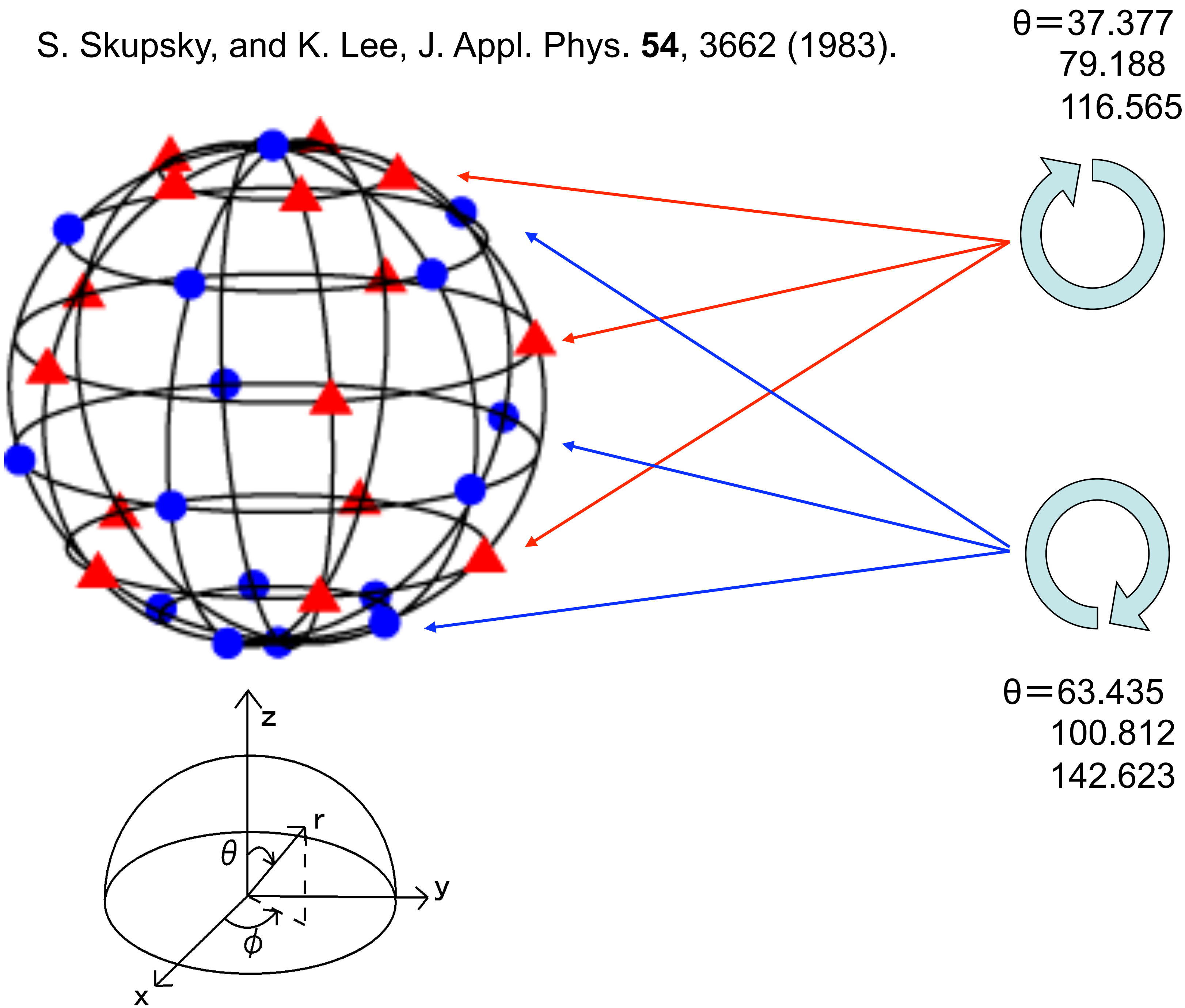
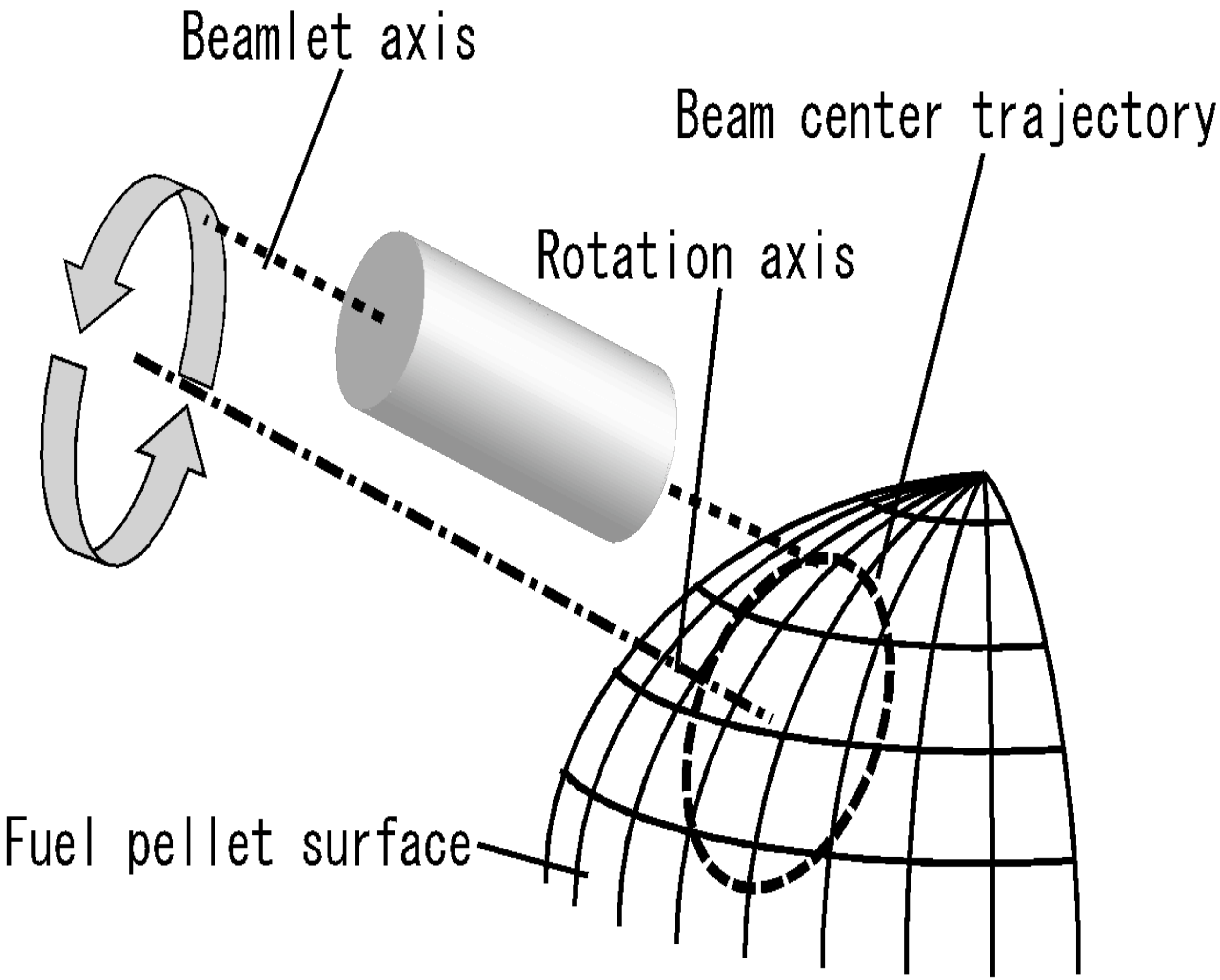
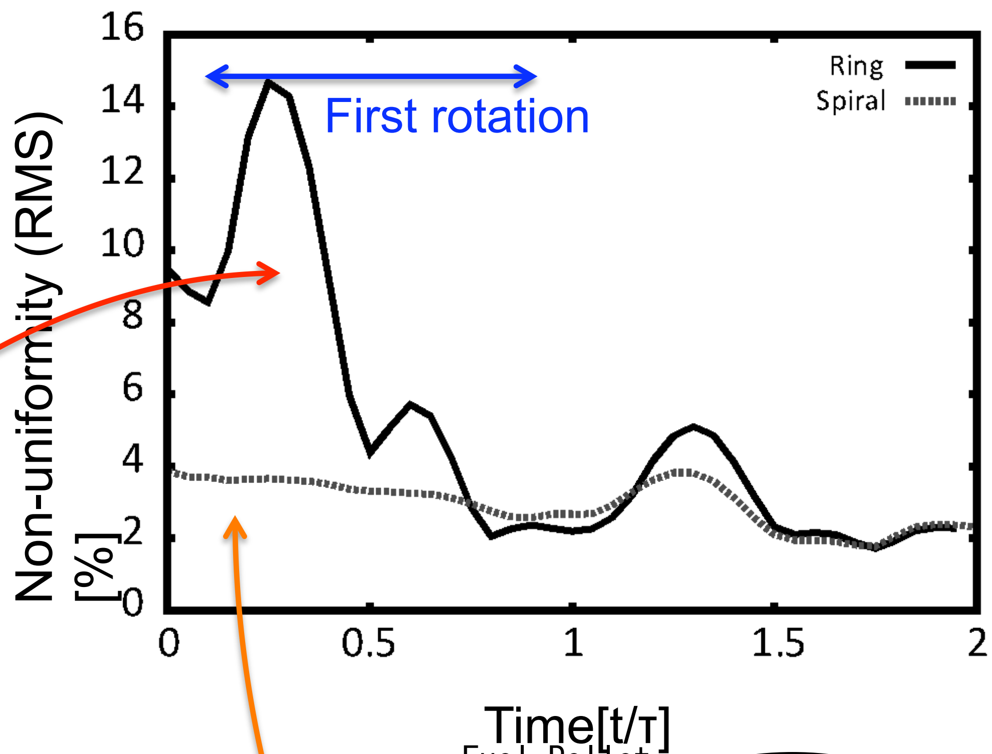


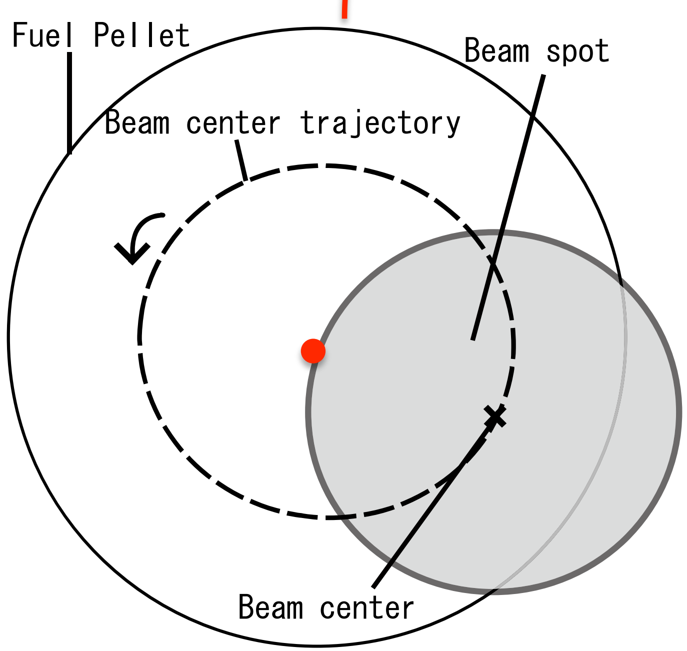
Image of Wobbling Heayv Ion Beam

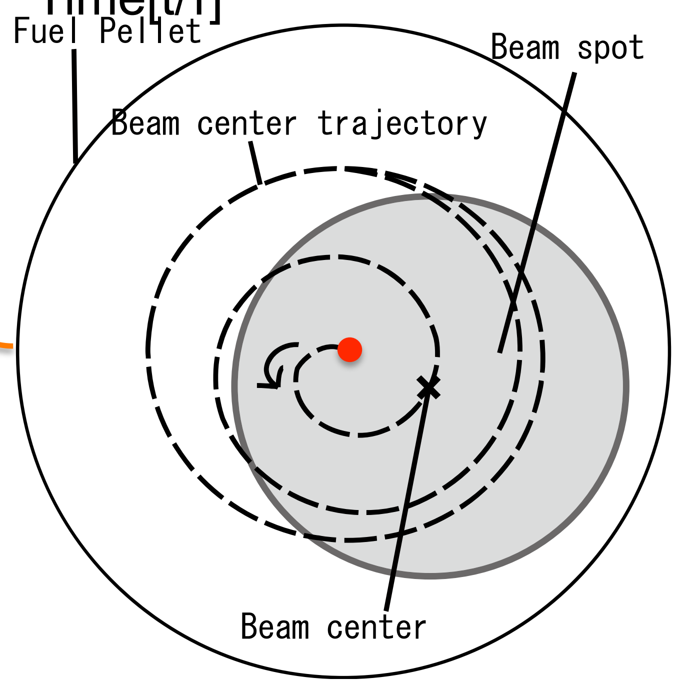


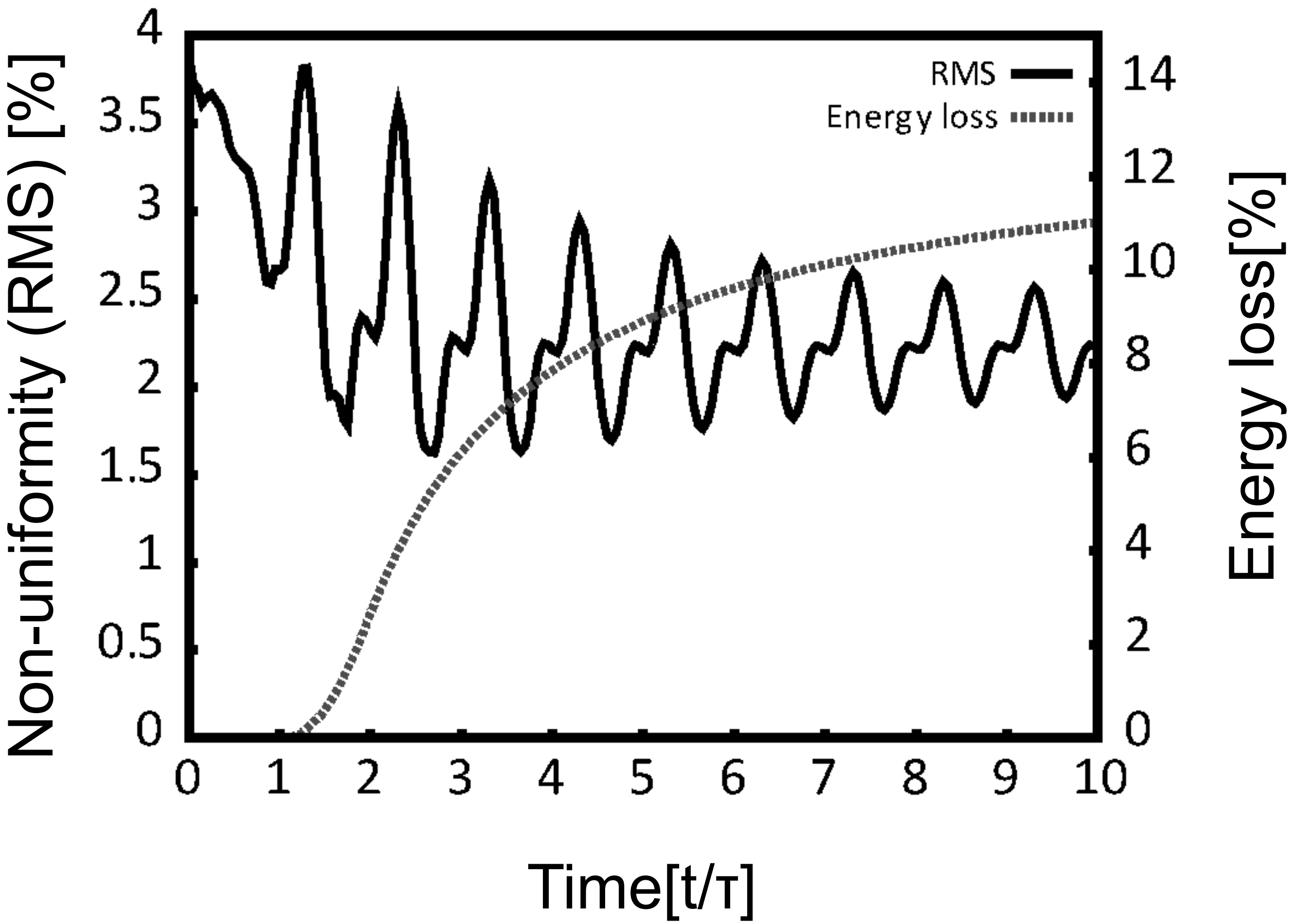
Initial imprint was huge.

<- Spiral HIBs reduce Imprint.

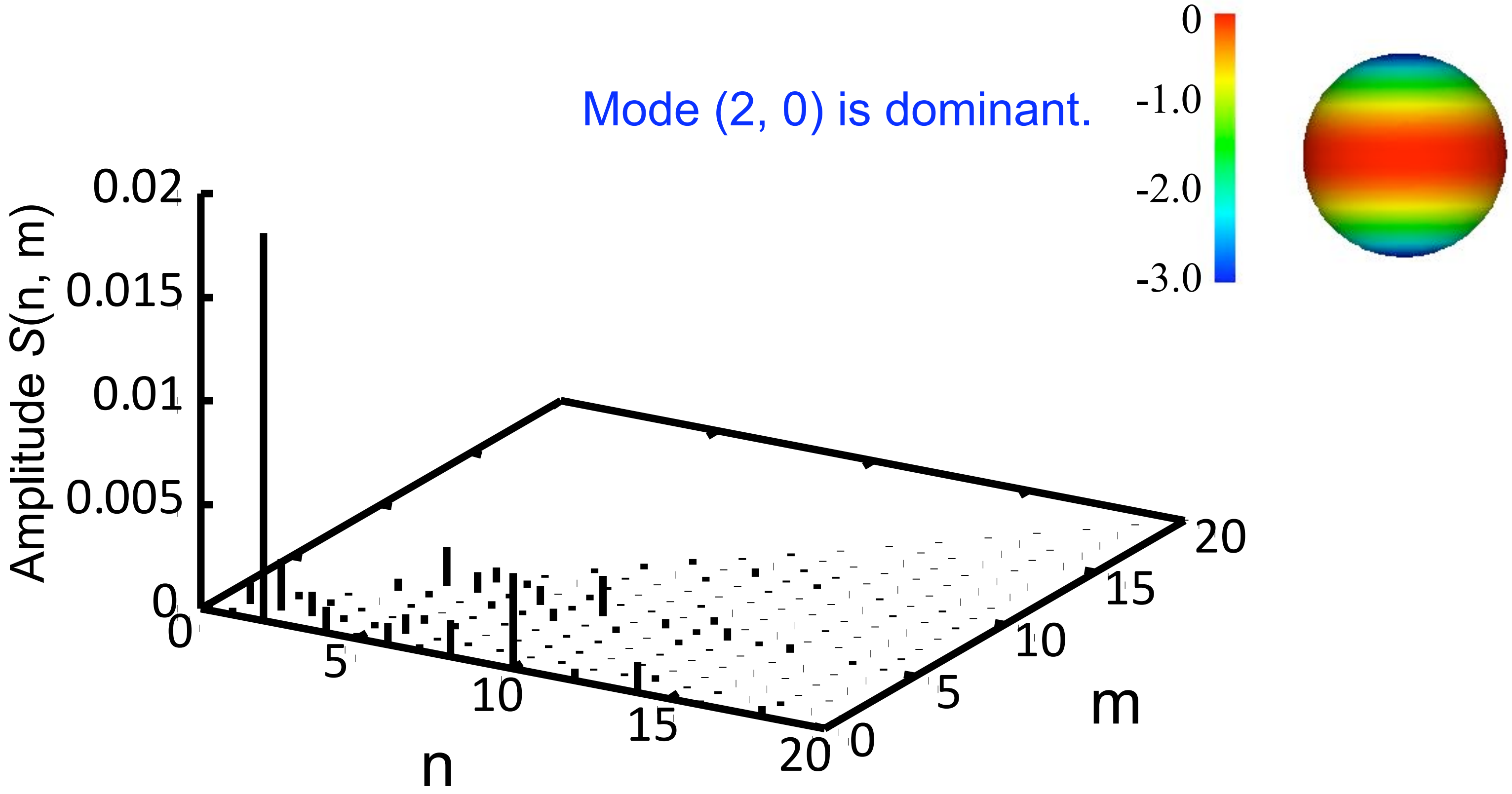




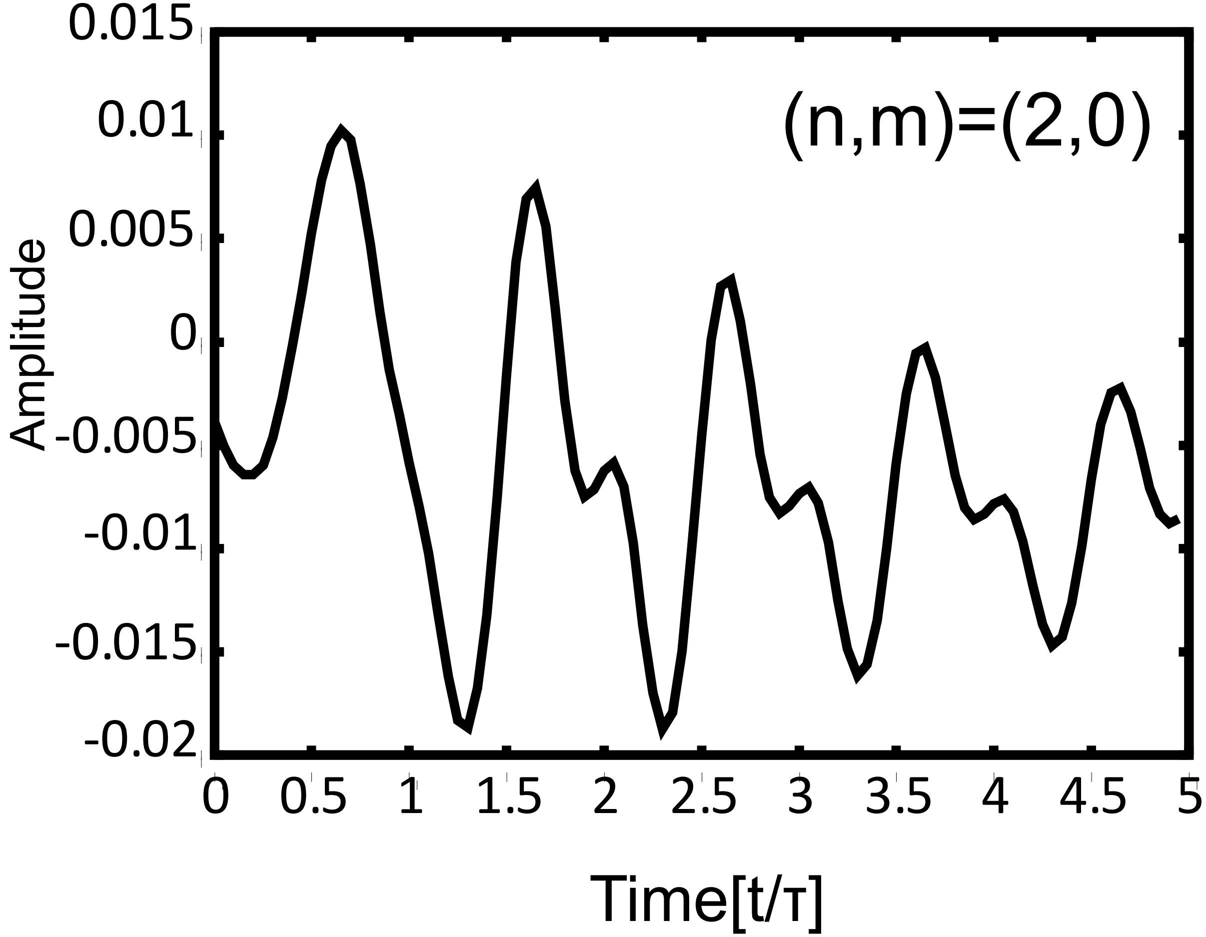




RMS
Energy loss
Non-uniformity (RMS) [%]
Energy loss[%]
Time[t/τ]
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
10
12
14
0
1
2
3
4
5
6
7
8
9
10

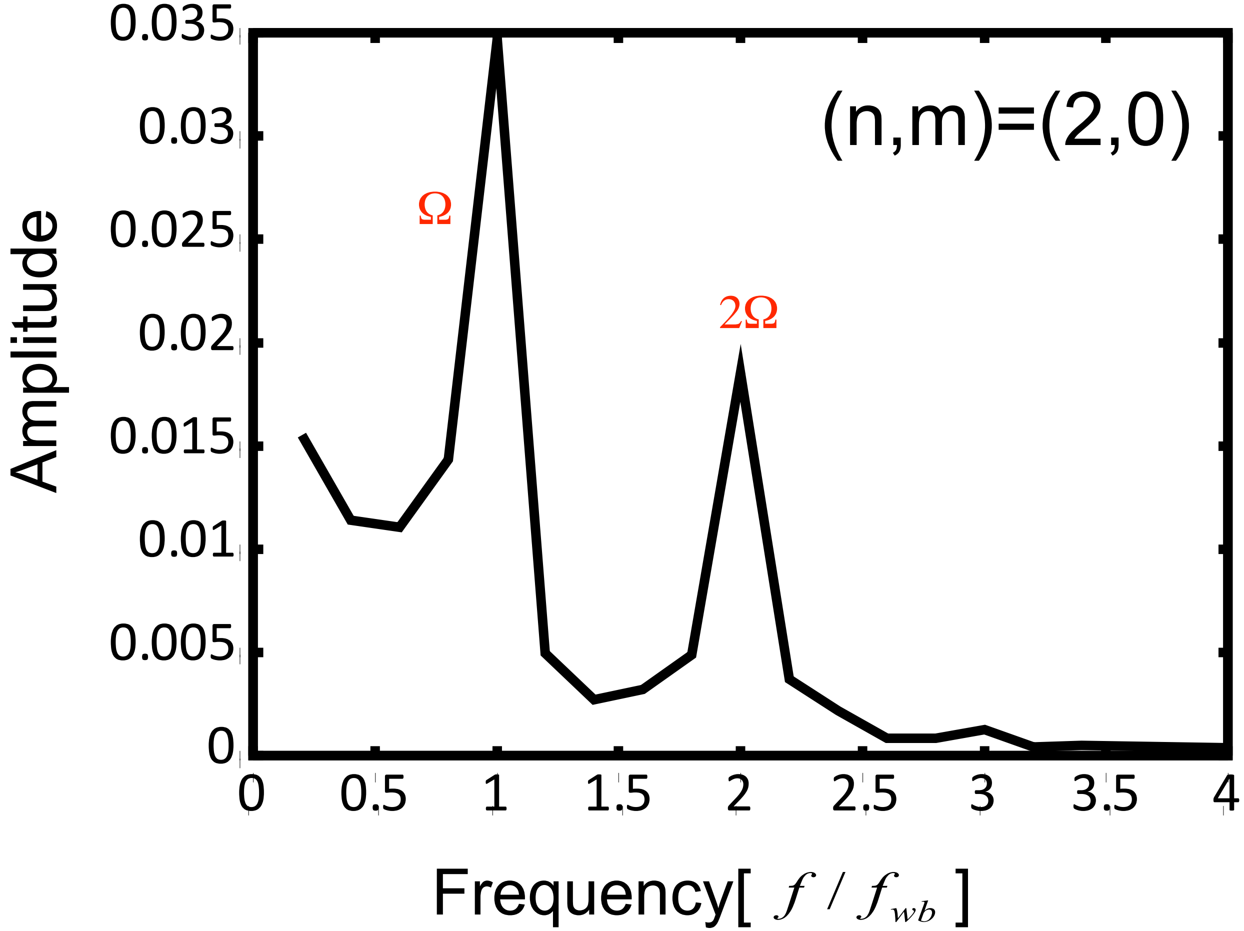


Mode (2, 0) is dominant.
0
-1.0
-2.0
-3.0
Amplitude S(n, m)
0.02
0.015
0.01
0.005
0
0
5
10
15
20
n
0
5
10
15
20
m



0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
Amplitude
(n,m)=(2,0)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time[t/τ]

A few % of energy deposition nonuniformity oscillates with the the wobbling HIBS oscillation frequency Ω.



Phys. Plasmas **19**, 063111 (2012)

Arc-based smoothing of ion beam intensity on targets

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The Virtu

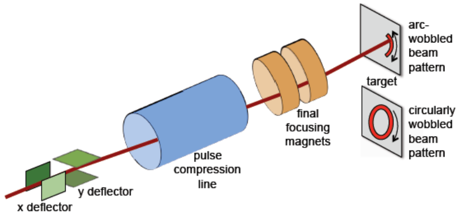

FIG. 1. Wobbler geometry, showing a single beam in the crossed-deflector system, the longitudinal bunch-compression line, the final-focus quadrupole magnet array, and impinging on the target. Both arc-wobbled and circularly-wobbled illumination patterns are shown.

FIG. 4. Sketch of "switchback" geometry for two-harmonic wobbler approach (see text).

PHYSICS OF PLASMAS VOLUME 11, NUMBER 4

On the symmetry of cylindrical implosions driven by a rotating beam of fast ions

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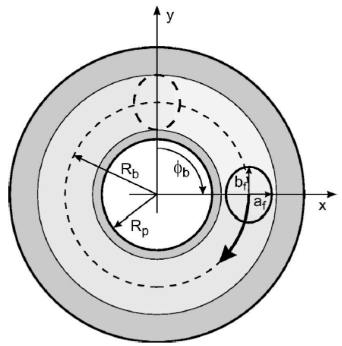

FIG. 1. Target configuration for cylindrical implosions driven by a rotating ion beam.

Summary

/ Spiral Wobbling HIBs introduce
a low illumination non-uniformity. < 3.8%
At steady state < 2.5%!

/ Initial imprint does not give a large nonuniformity.

HIB main pulse ~ 10 - 20 nsec
Rotation frequency ~ several 100MHz~1GHz
=>
We found a time-dependent wobbling HIBs illumination
with a sufficient uniformity
+ with a time-dependent small nonuniformity
with the the wobblers oscillation frequency Ω.
-> may induces $g=g_0+\delta g$
-> Wobbling HIBs may give a new smoothing & R-T growth mitigation method!

32 HIBs ref.: Skupsky & Lee, JAP 54(1983)3662.

Θ	φ
0	0
37.377	0,72,144,216,288
63.435	36,108,180,252,324
79.188	0,72,144,216,288
100.812	36,108,180,252,324
116.565	0,72,144,216,288
142.623	36,108,180,252,324
180	0